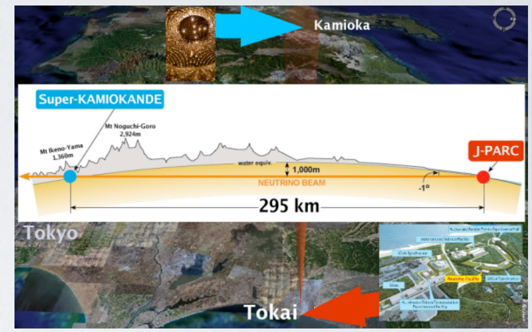
Inclusive Neutrino-Nucleus Scattering:

- Motivation
- Review of electron scattering
- Results for A=4, 12
- Moving toward heavier nuclei



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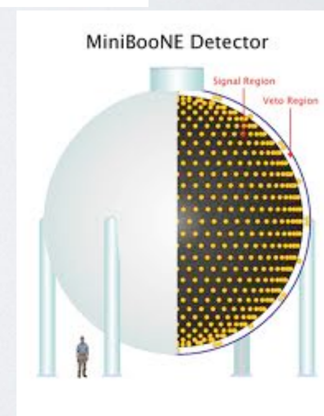
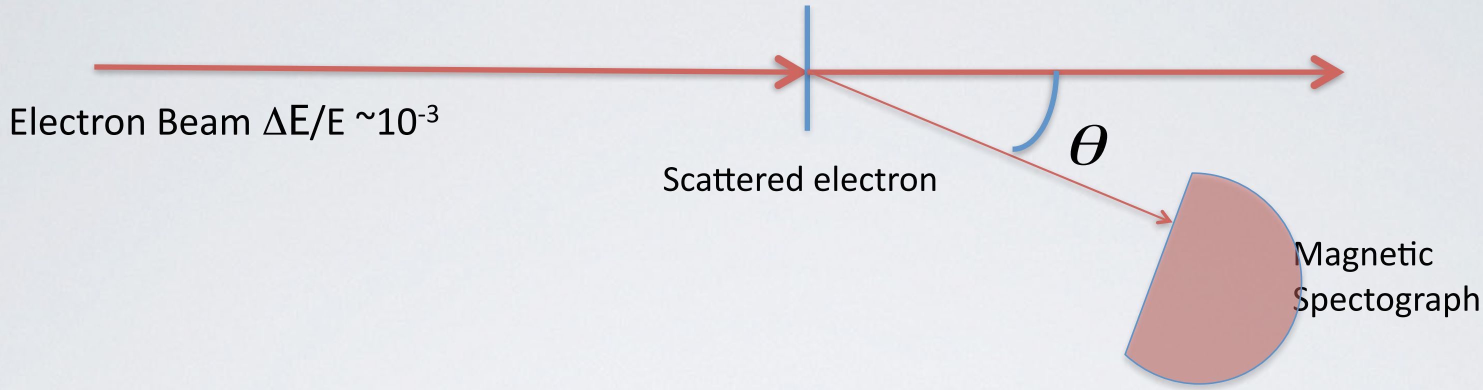
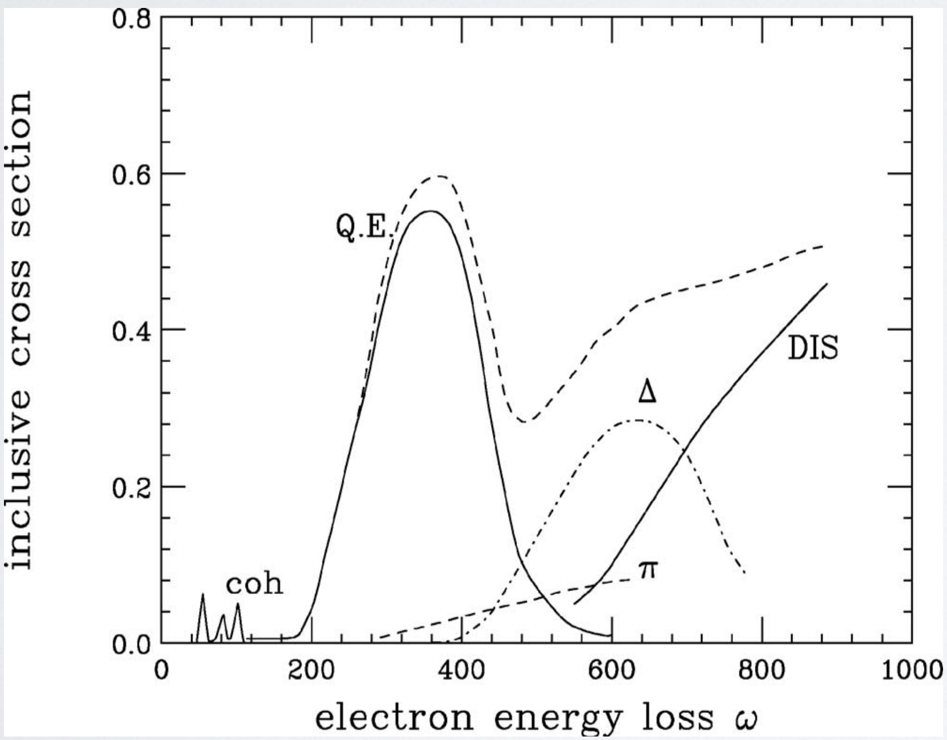


Important for all ≤ GeV neutrino experiments
LBNE, T2K, mini/micro-Boone, Nova, Minerva

Inclusive Electron Scattering





$$(E,0,0,p),\ \ (E',p'\sin\theta,0,p'\cos\theta)$$

$$\omega \equiv E - E'$$

$$\vec{q} = \vec{p} - \vec{p}\,'$$

Thus q and ω are precisely known <u>without any reference to the nuclear final state</u>

from Benhar, Day, Sick, RMP 2008

Inclusive Scattering

$$\frac{d^2\sigma}{d\Omega_{e'} dE_{e'}} = \left(\frac{d\sigma}{d\Omega_{e'}}\right)_M \left[\frac{Q^4}{|\mathbf{q}|^4} R_L(|\mathbf{q}|,\omega) + \left(\frac{1}{2}\frac{Q^2}{|\mathbf{q}|^2} + \tan^2\frac{\theta}{2}\right) R_T(|\mathbf{q}|,\omega) \right]$$

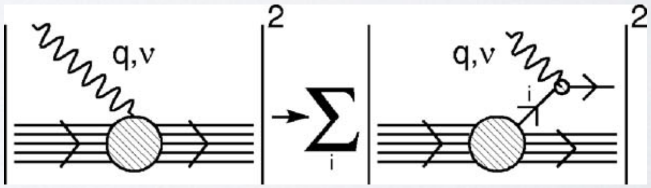
electron scattering

$$R(q,\omega) \ = \ \sum_f \langle 0|\ \mathbf{j}^\dagger(q)\ |f\rangle\langle f|\ \mathbf{j}(q)\ |0\rangle\ \delta(w - (E_f - E_0))$$

$$R(q,\omega) \ = \ \int dt\ \langle 0|\ \mathbf{j}^\dagger(q)\ \ \exp[i(H-\omega)t]\ \mathbf{j}(q)\ |0\rangle$$

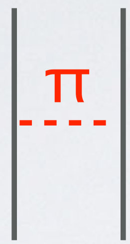
Full Response: Ground State (Hamiltonian)
Currents
Propagation for final states

Impulse Approximation for quasi-elastic
incoherent sum over single nucleons
requires momentum distributions and spectral functions



What is needed?

Hamiltonian: two-nucleon (+ 3 nucleon) interactions



Currents: 1 + 2-nucleon currents + …

virtual pions, deltas, …

yields ground state, current, FSI, …

Same model for beta-decay, astrophysical neutrinos, double-beta decay, accelerator neutrinos

Simple view of Nuclei: inclusive scattering

Charge distributions of different Nuclei:

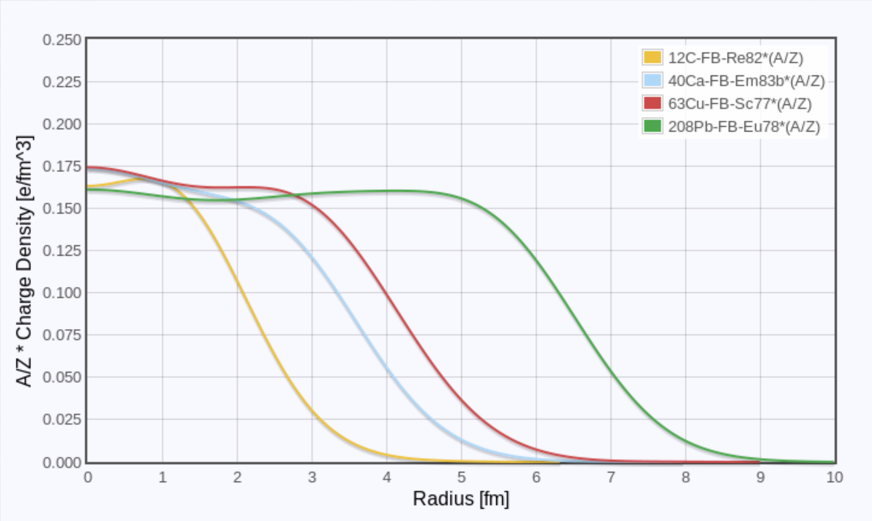
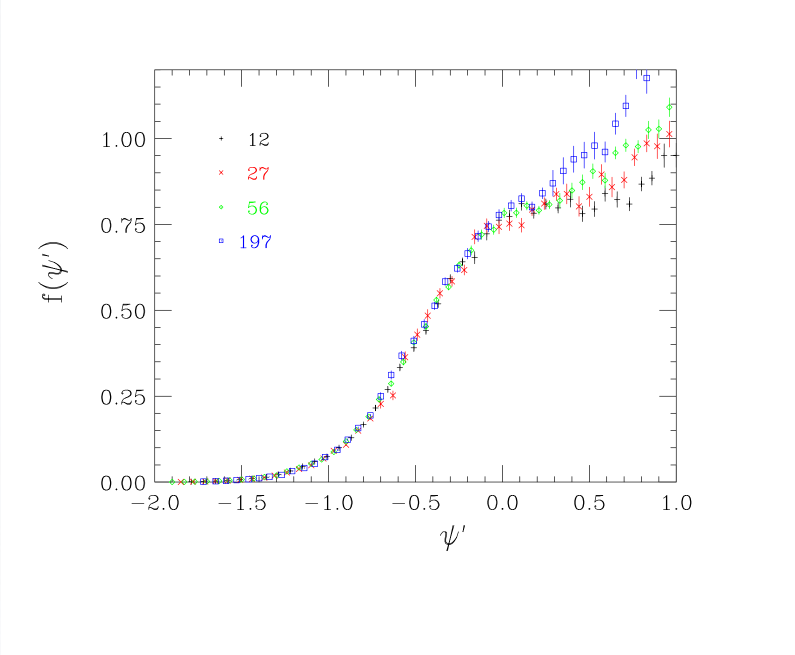


figure from faculty.virginia.edu/ncd
based on work of Hofstadter, et al.: Nobel Prize 1961

Scaling (2nd kind) different nuclei

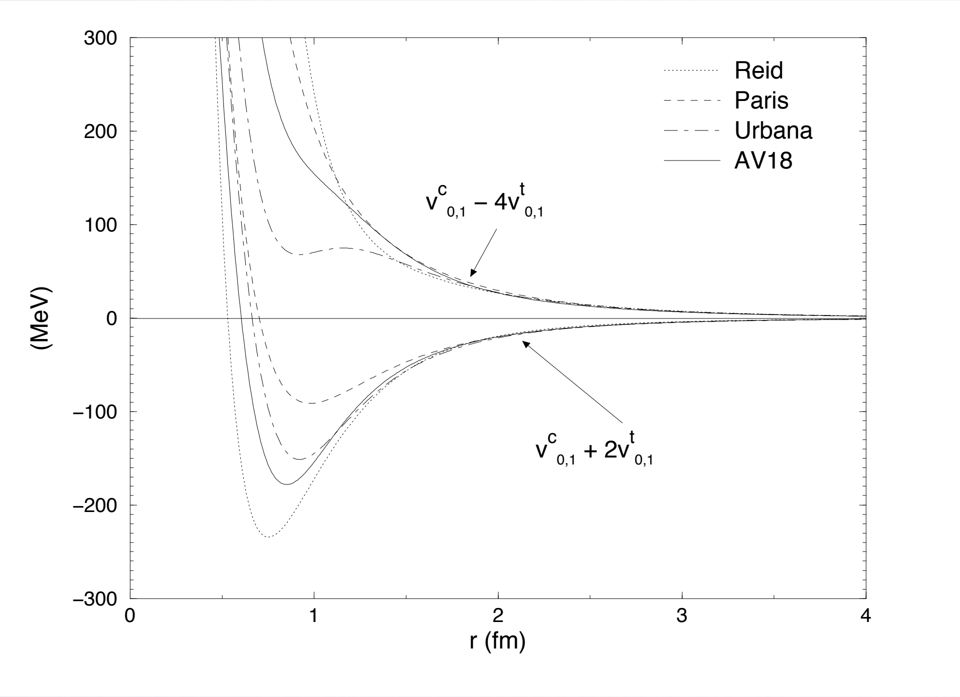


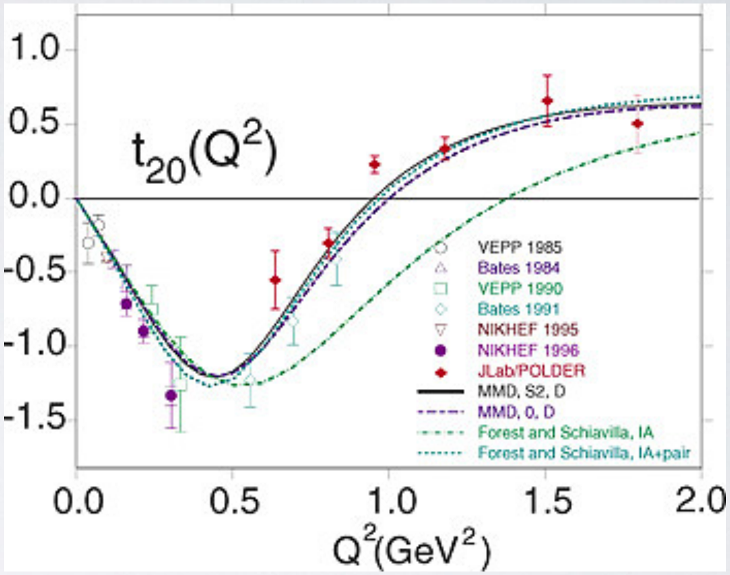
Donnelly and Sick, 1999

Inclusive scattering measures properties at distances ~ $\pi / q \lesssim 1$ fm

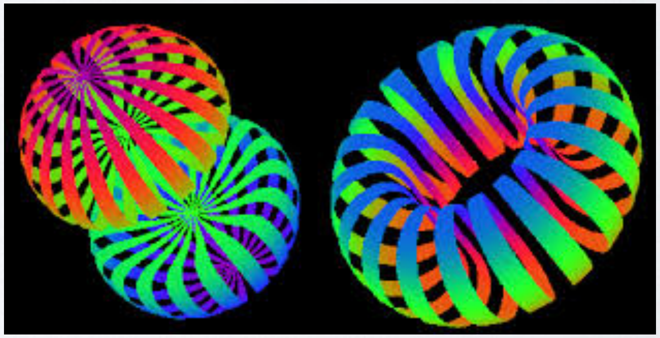
Nucleon-Nucleon Interactions

Deuteron Potential Models with Different Spin Orientations





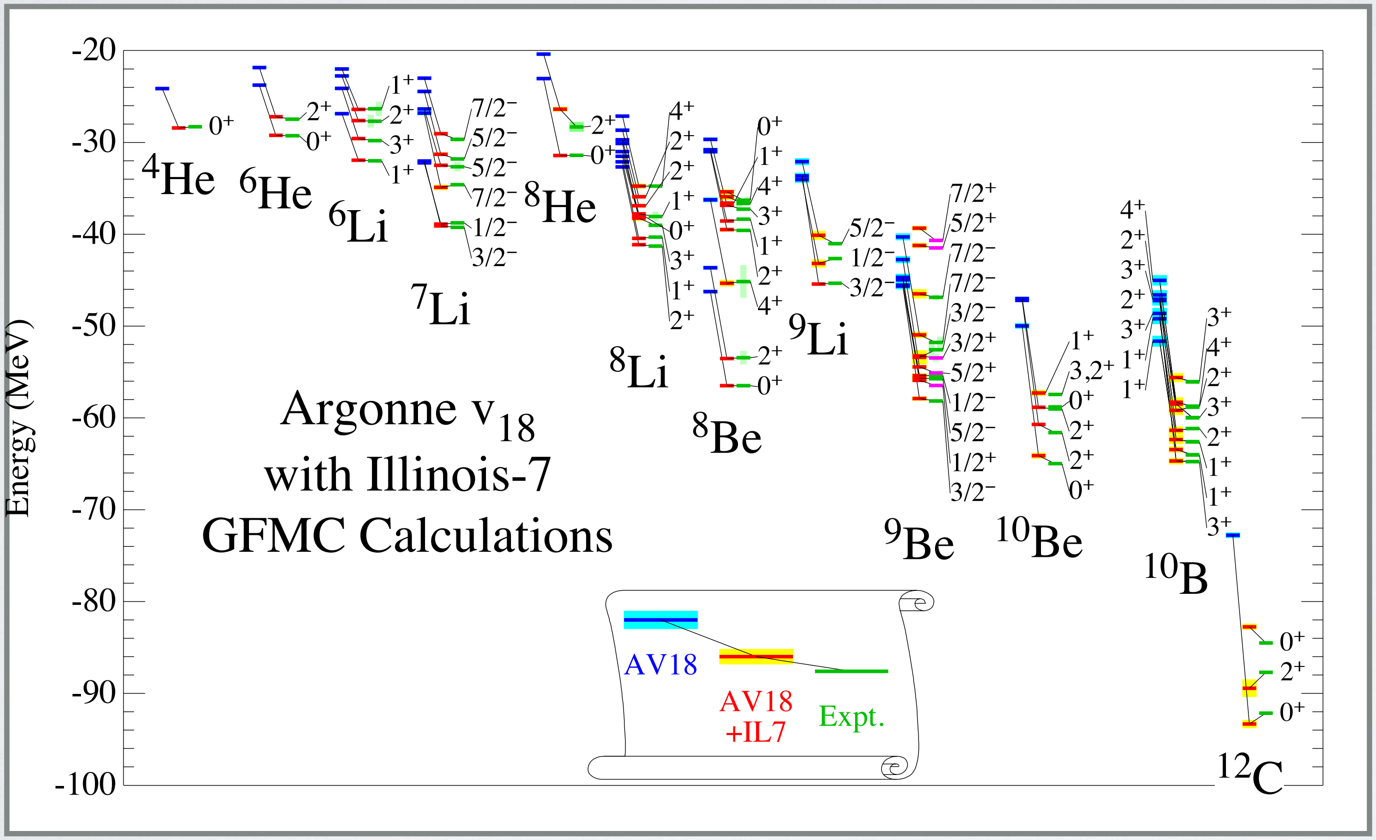
t20 experiment Jlab R. Holt



Forrest, et al, PRC 1996

Ground States

- Non-relativistic nucleons only model
- AV18 + 3-nucleon interactions
- Includes pion exchange and fits phase shifts to fairly high energies (elastic threshhold)
- Also fits low energy properties of nuclei



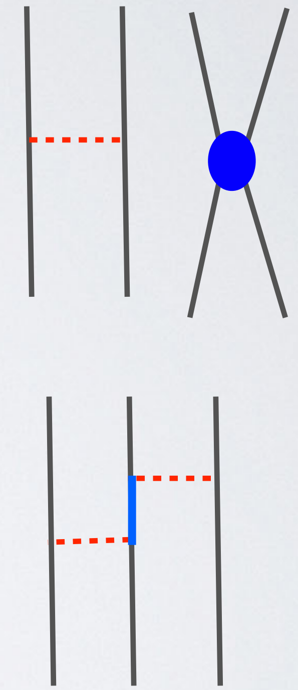
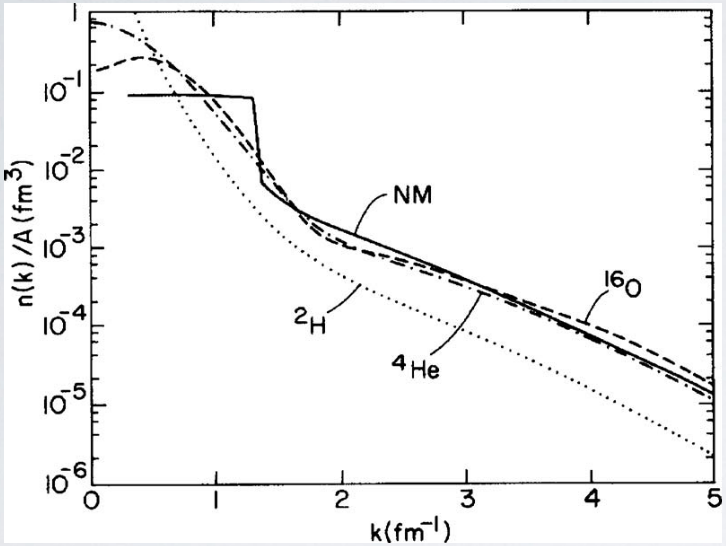


FIG. 2 GFMC energies of light nuclear ground and excited states for the AV18 and AV18+IL7 Hamiltonians compared to experiment.

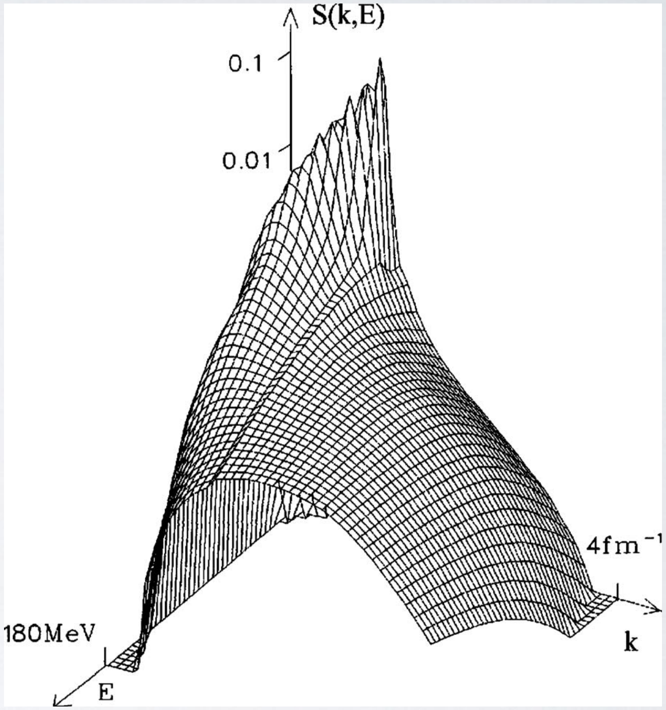
Carlson, et al, arXiv:1412.3081

Momentum Distributions and Spectral Functions



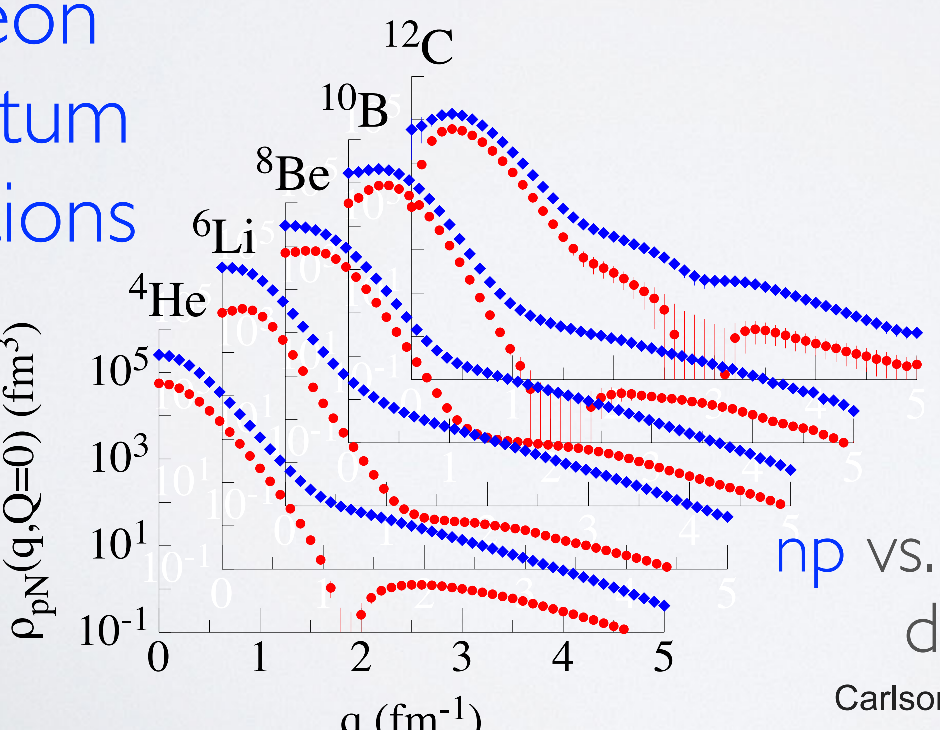
Schiavilla, et al 1986, Benhar, et al 1993

Spectral Function in NM



Benhar, 1989

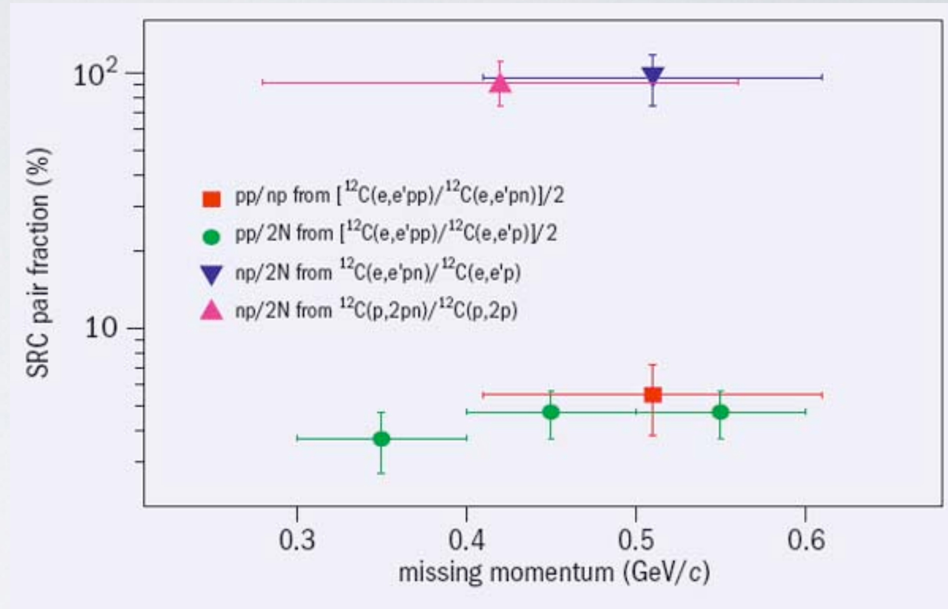
2-nucleon momentum distributions

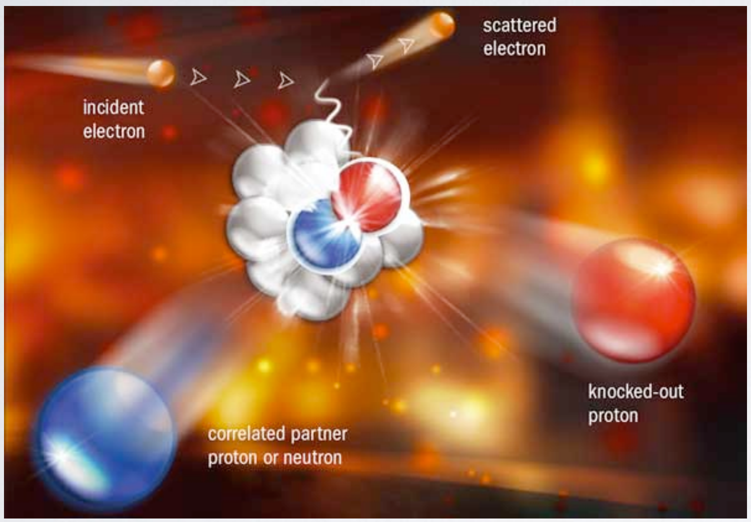


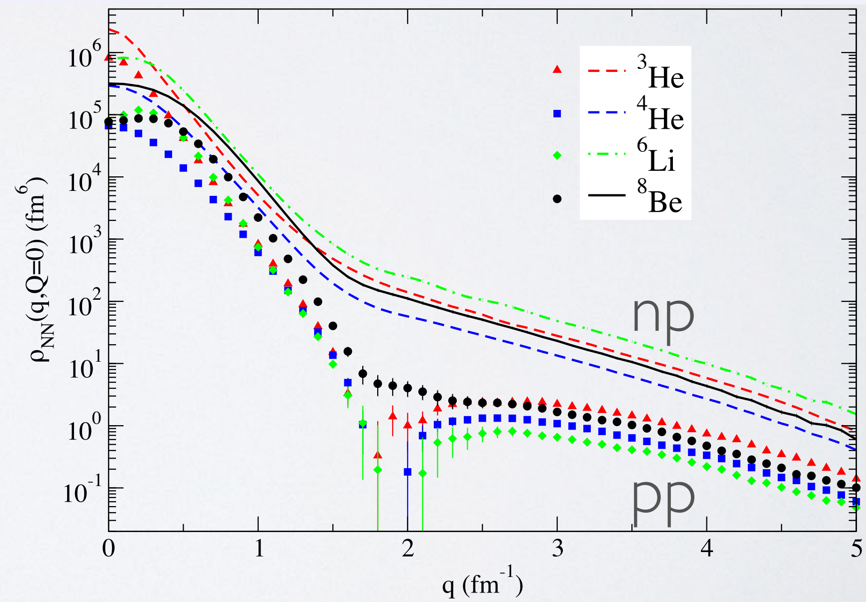
np vs. pp momentum distributions

Carlson, et al, arXiv:1412.3081

JLAB, BNL back-to-back pairs in 12C
np pairs dominate over nn and pp







E Piasetzky *et al.* 2006 **Phys. Rev. Lett. 97** 162504.

M Sargsian *et al.* 2005 **Phys. Rev. C 71** 044615.

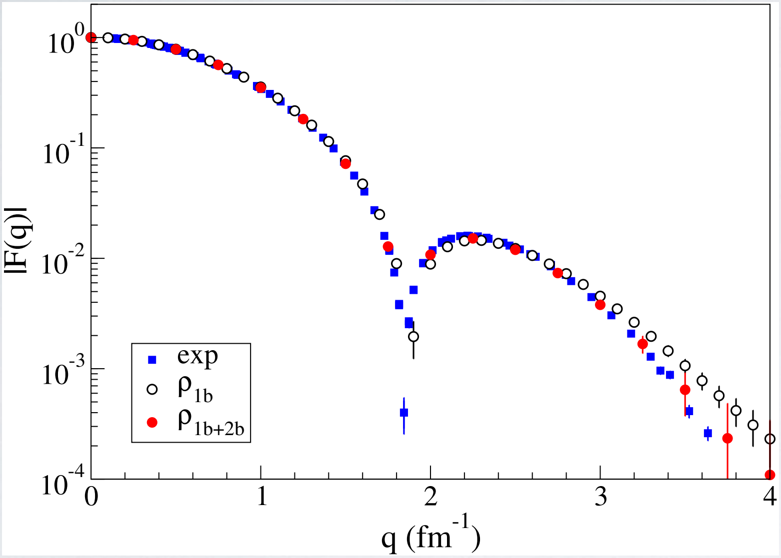
R Schiavilla *et al.* 2007 **Phys. Rev. Lett. 98** 132501.

R Subedi *et al.* 2008 **Science 320** 1475.

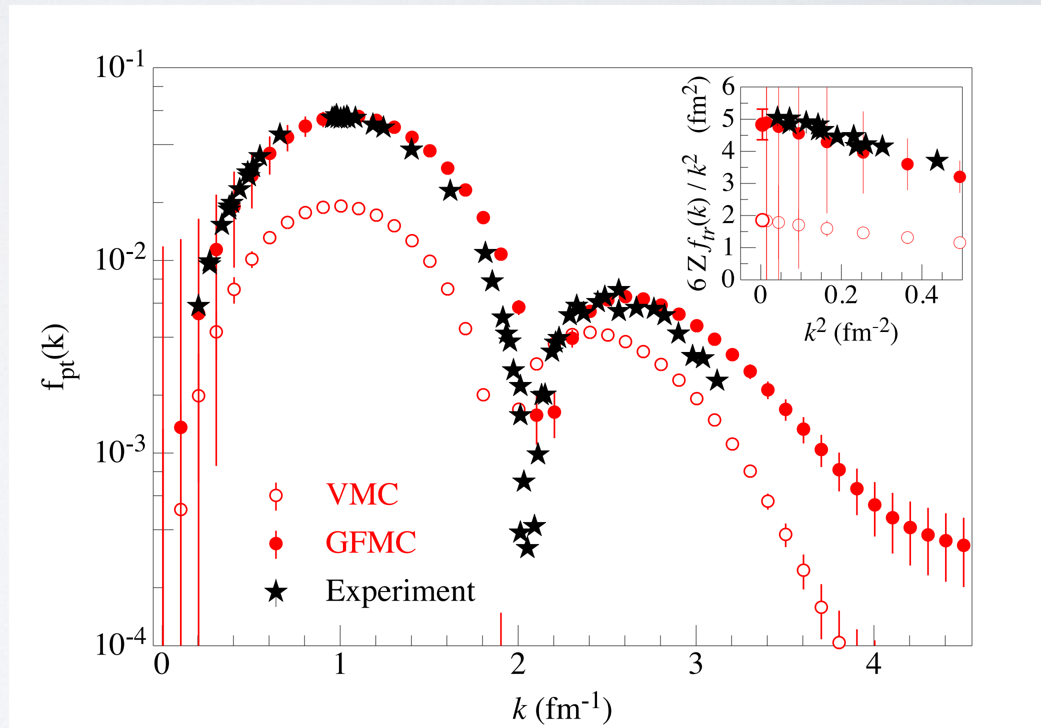
P=0 pair momentum distributions

Currents

^{12}C elastic form factor

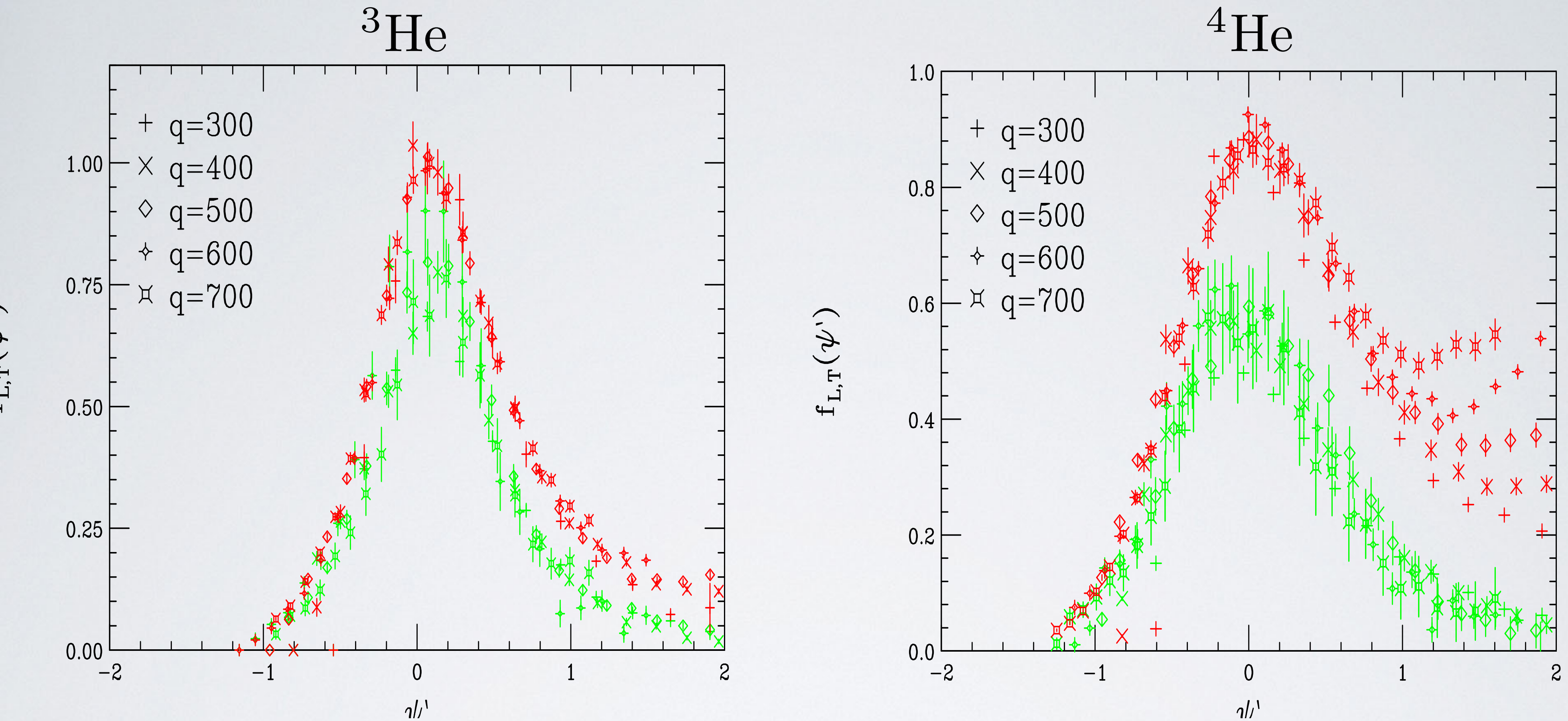


Hoyle state transition form factor



(e, e') Inclusive Response: Scaling Analysis

Donnelly and Sick (1999)



Single nucleon couplings factored out

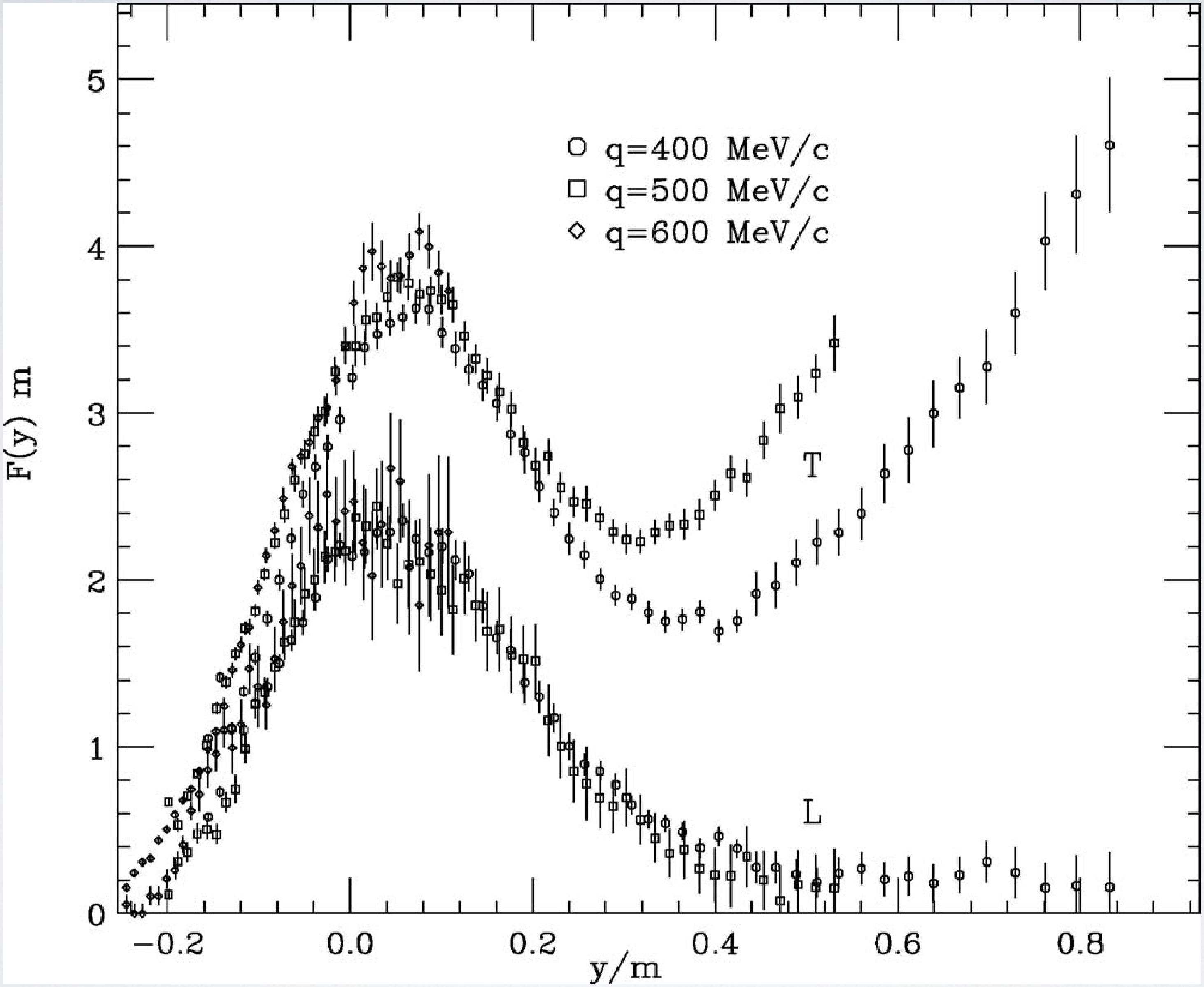
Momenta of order inverse internucleon spacing:

Large enhancement of transverse over longitudinal response

Requires beyond single nucleon physics;

spectral function alone will not work

Longitudinal/Transverse separation in ^{12}C



from Benhar, Day, Sick, RMP 2008
data Finn, et al 1984

Microscopic (non-relativistic nucleons) approach:

- Interactions fit to NN scattering data
- `Realistic' models of two-nucleon currents
- Calculate response with full inclusion of final-state interactions and two-nucleon currents

Disadvantages: (can be improved)

non-relativistic nucleons

no pion production or Δ production

Advantages:

same treatment for initial and final states

include full realistic interactions fit to NN data

with simultaneous two-nucleon currents

What we can compute reliably (given the model)

$$R_{L,T}\ (q,\omega)\ = \sum_f \delta(\omega\ +\ E_0\ + E_f)\ |\ \langle\ f\ |\mathcal{O}_{\mathcal{L},\mathcal{T}}\ |\ 0\ \rangle\ |^2$$

Easy to calculate Sum Rules: ground-state observable

$$S(q)\ =\ \int d\omega\ R(q,\omega) = \langle 0|O^\dagger(q)\ O(q)|0\rangle$$

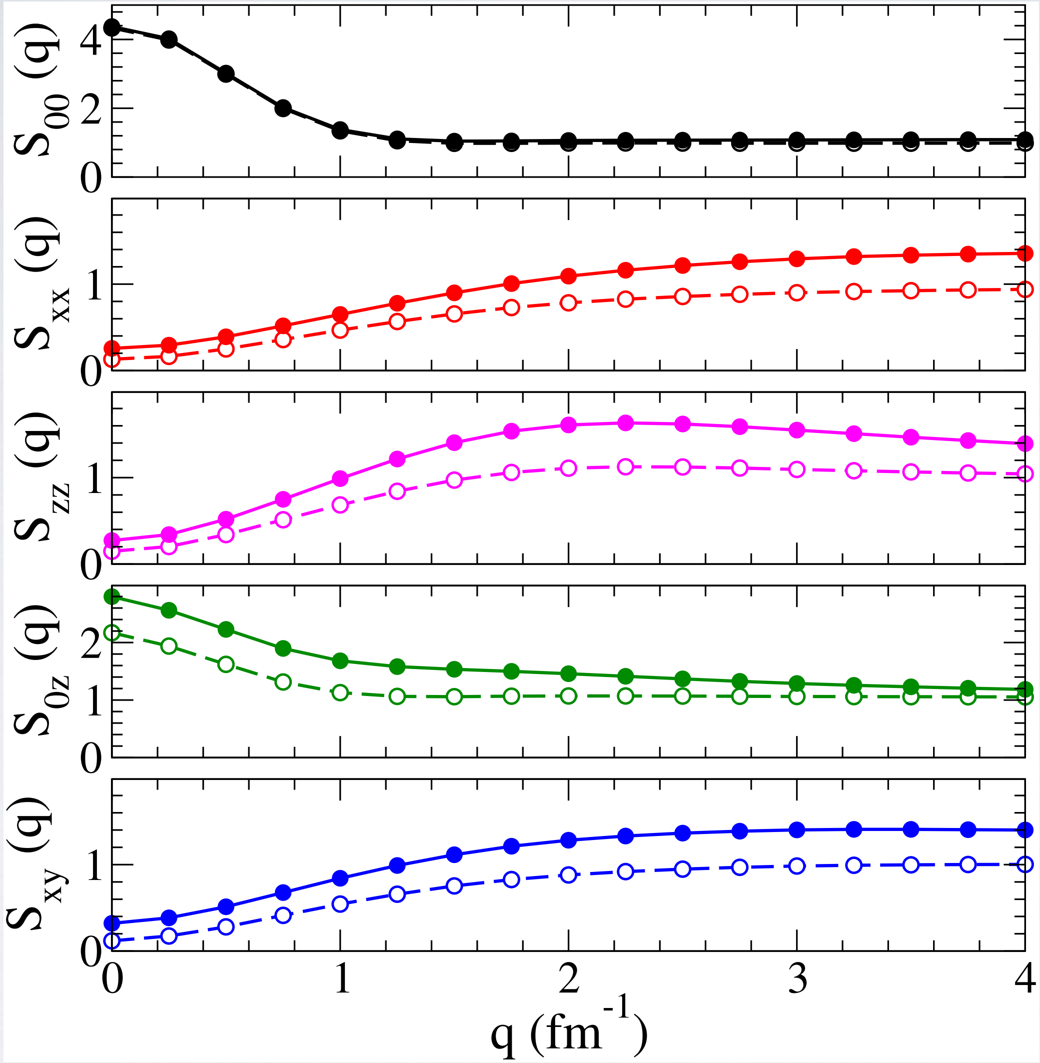
Imaginary Time (Euclidean Response)
statistical mechanics

$$\tilde{R}(q,\tau)\ =\ \langle 0|\ \mathbf{j}^\dagger\ \exp[-(\mathbf{H}-\mathbf{E_0}-\mathbf{q^2}/(\mathbf{2m}))\tau]\ \ \mathbf{j}\ |\mathbf{0}\rangle >$$

$$H\ = \sum_i \frac{p_i^2}{2m}\ + \sum_{i<j} V_{ij}\ + \sum_{i<j<k} V_{ijk}$$

$$\mathbf{j}\ = \sum_i \mathbf{j}_i\ + \sum_{i<j} \mathbf{j}_{ij} + ...$$

Sum rules in 12C

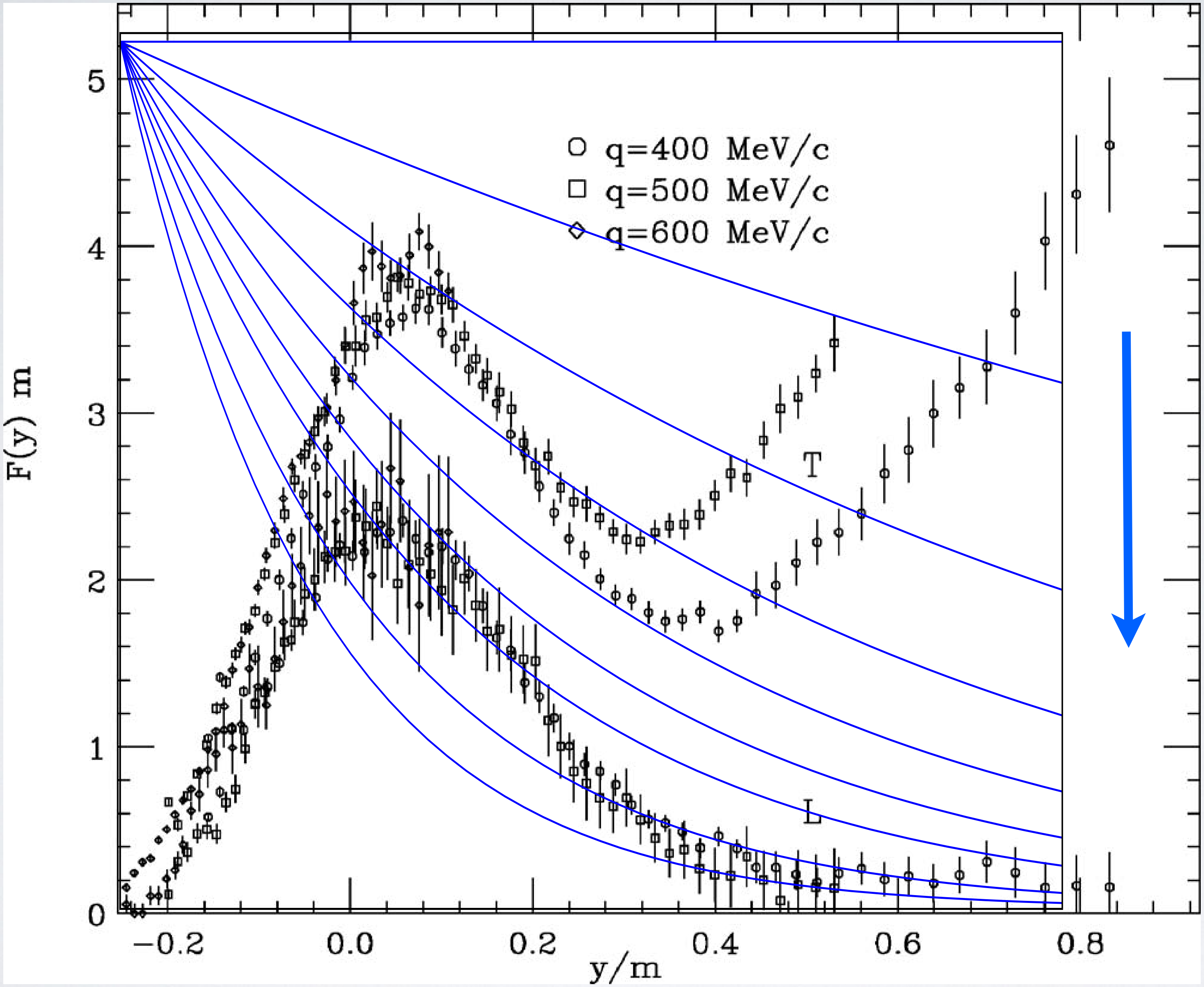


EM

Lovato, et. al PRL 2014

Single Nucleon currents (open symbols) versus
Full currents (filled symbols)

Euclidean Response



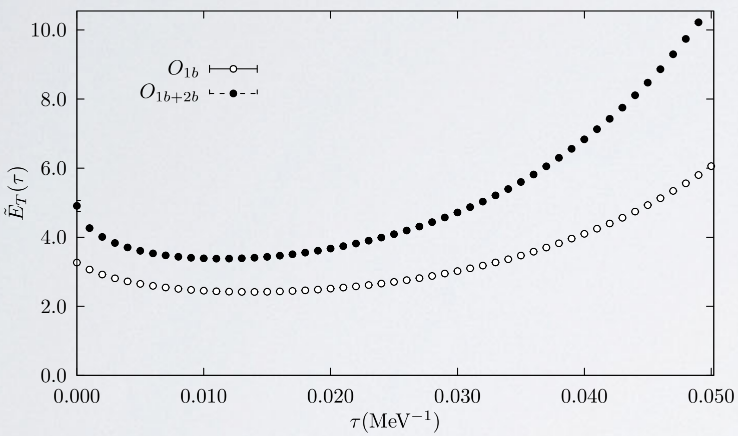
τ = inverse T

Sum rule → elastic FF^2 w/ increasing τ

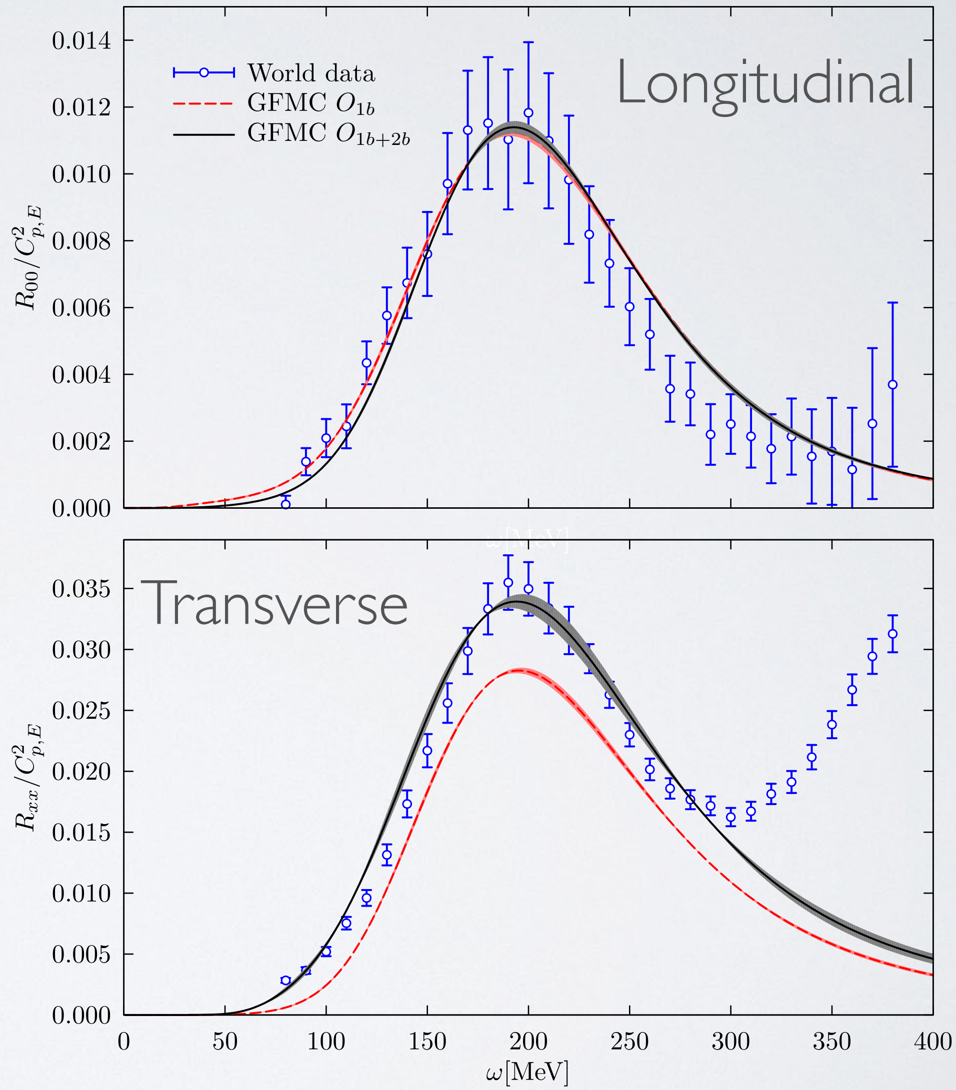
A=4 EM response

Euclidean

q = 500 MeV



q = 600 MeV

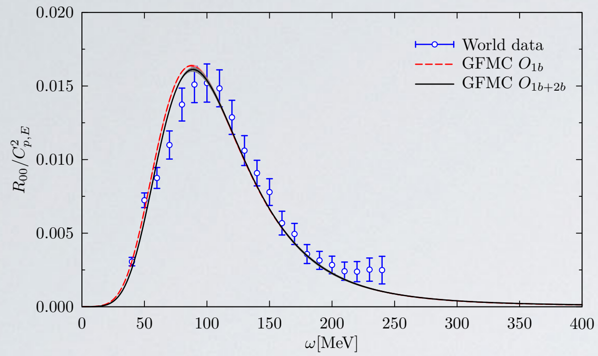


Lovato, et al, arXiv:1501.01981

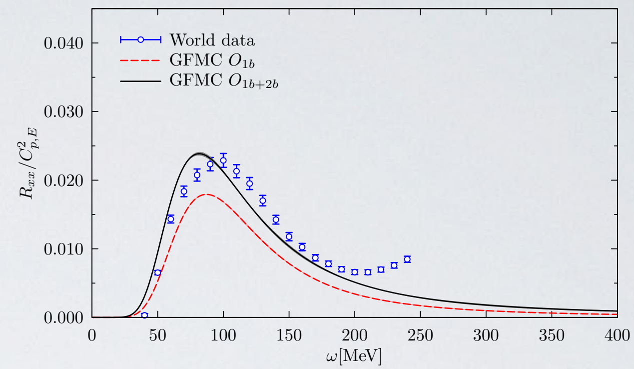
^{4}He EM

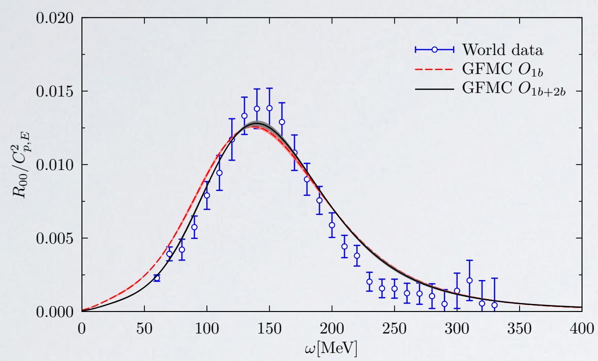
Longitudinal

Transverse

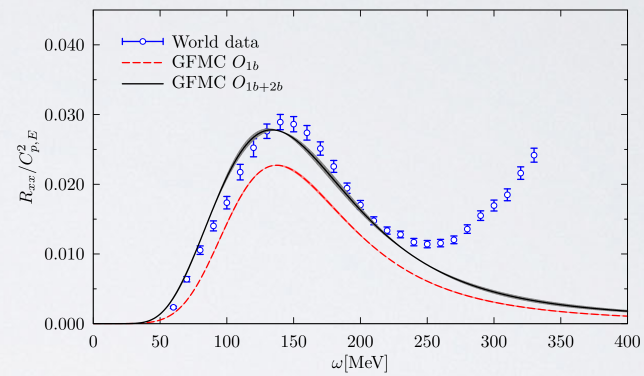


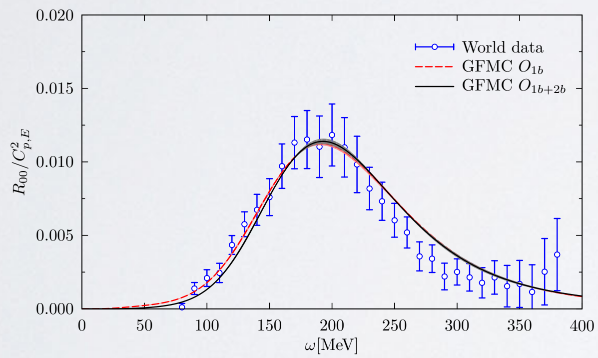
q=400



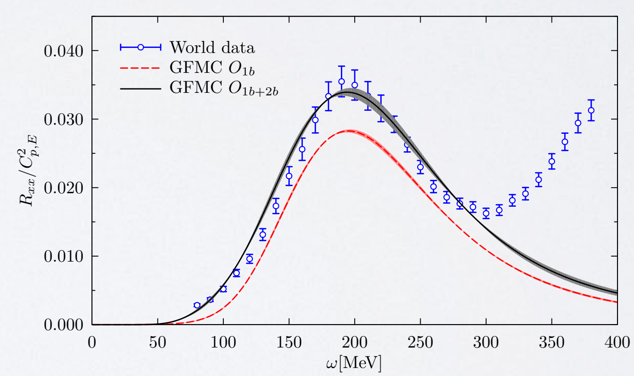


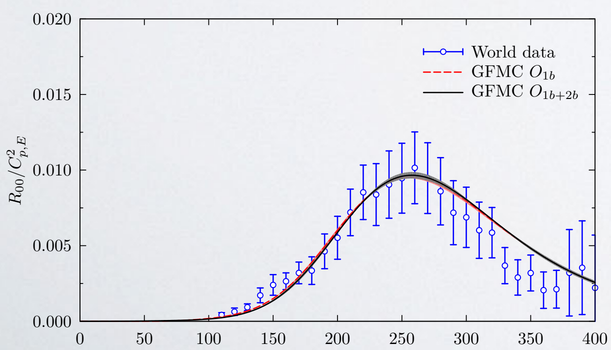
500



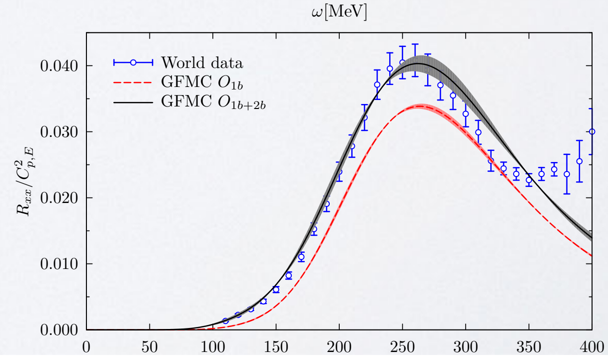


600

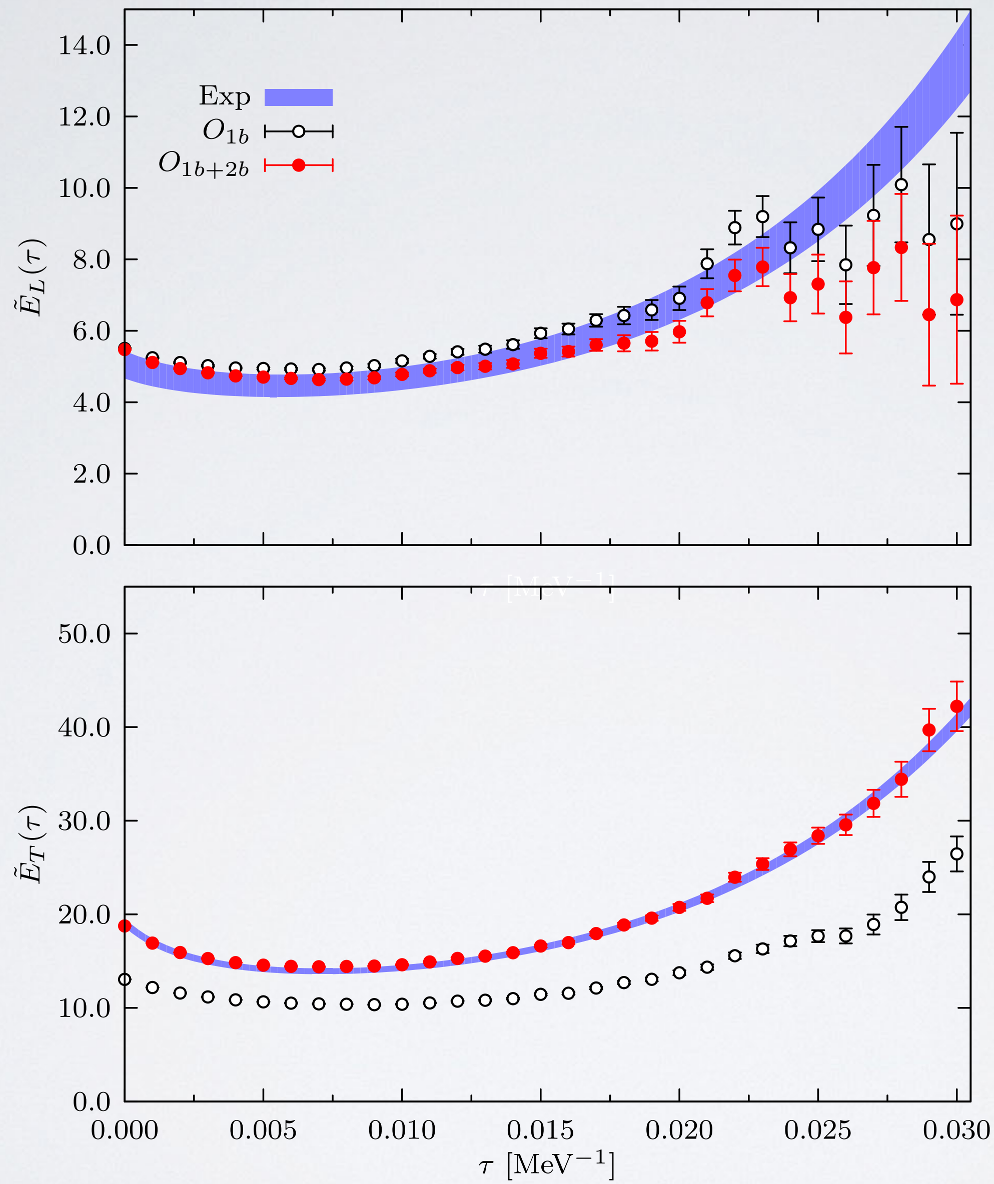




700

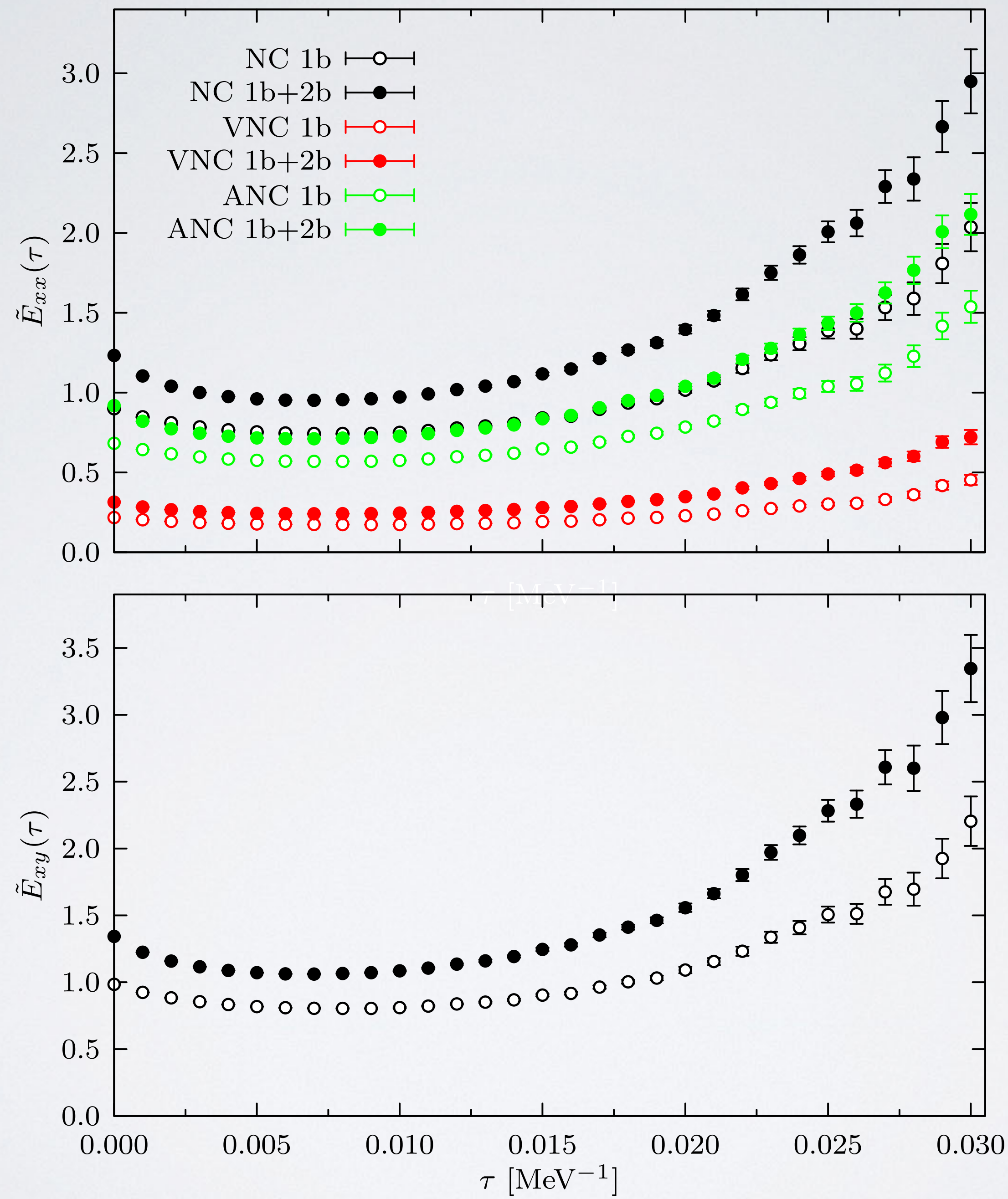


12C Euclidean Response: EM



Lovato, et al, arXiv:1501.01981

^{12}C Euclidean Response: Neutral Current



Lovato, et al, arXiv:1501.01981

Larger Nuclei: Argon

Two (complimentary) approaches:

Quantum Monte Carlo for Larger Nuclei (AFDMC, sample spins and isospins)

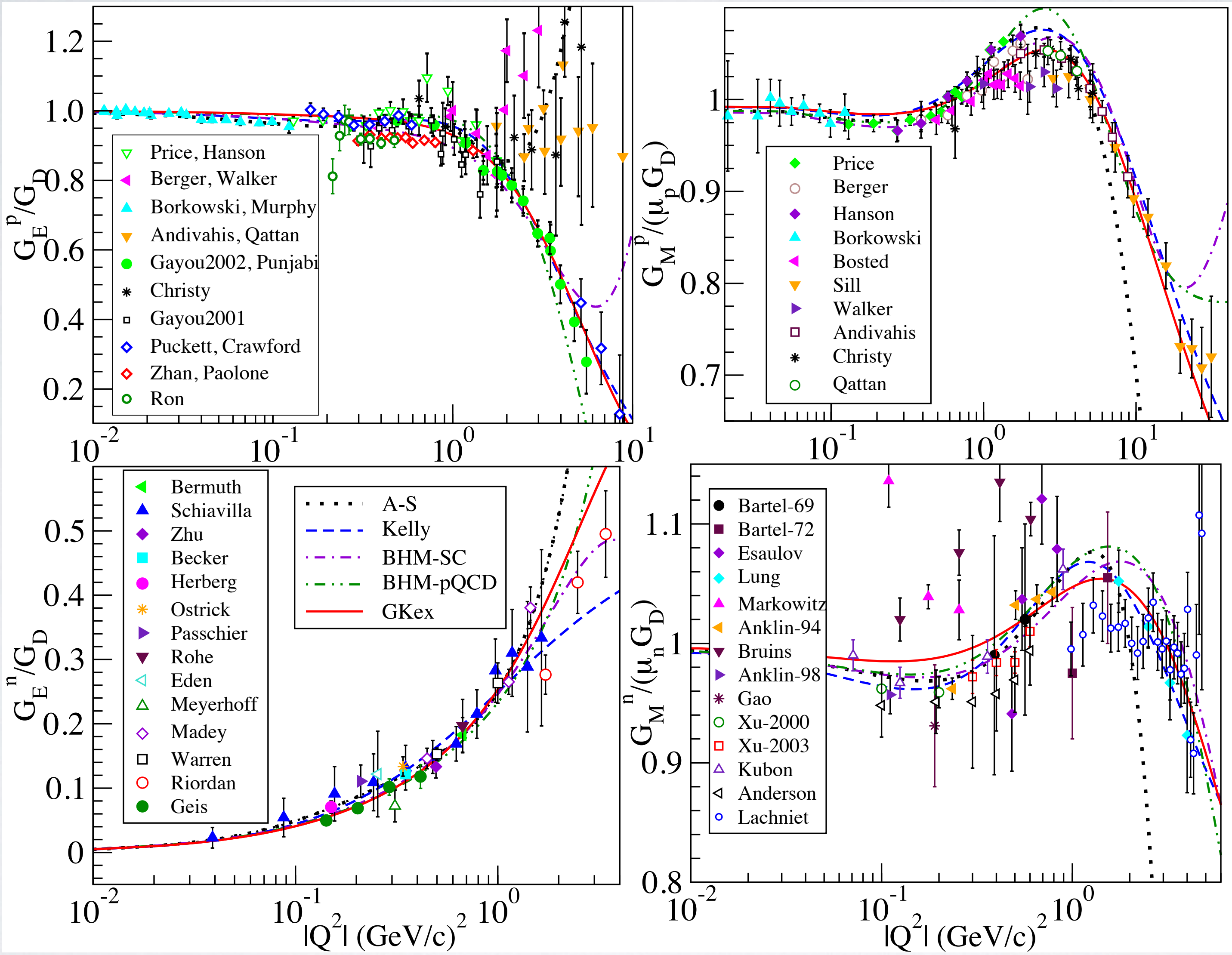
Ground states, momentum distributions,
sum rules, Euclidean Response

Factorization Approaches at two-nucleon level
keep two-nucleon dynamics exactly (interactions, current)
global constraints from QMC approaches (sum rules, Euclidean)
improvable: relativistic kinematics, Deltas, …

Thanks to:
ANL devoting ~100M core-hours to this project plus staff/postdoc time
NULEI SciDAC-3 project (computingnuclei.org)
INCITE award to NUCLEI project amount largest in country
- neutrino scattering is an important goal
LANL support through LDRD-DR and LDRD-ER Projects

Backup Slides

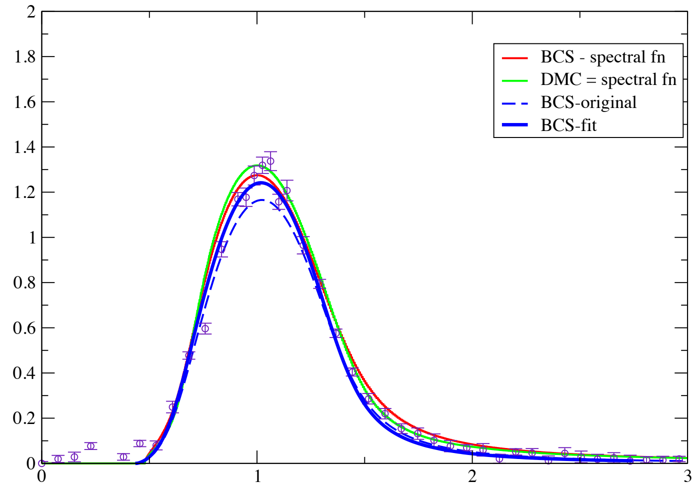
Nucleon Form Factors



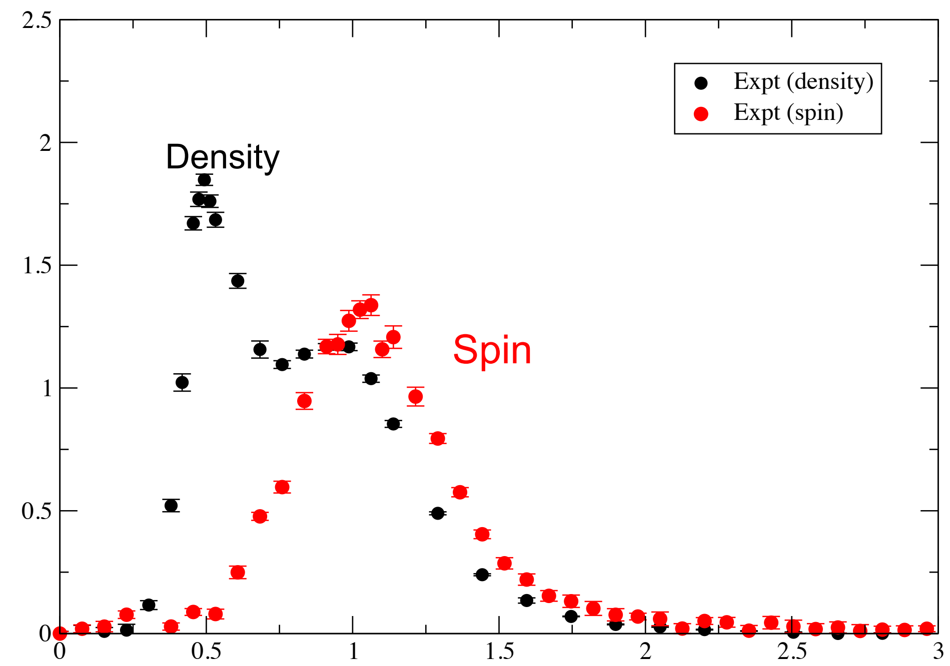
Gonzalex-Jiminez, Caballero, Donnelly, Phys. Reports 2013

Cold Atoms (Fermions at Unitarity)

Spin Response : Spectral Function Approach



Spin versus Density response (Experiment)



Both at q = 4.5 kF

Density and Spin Response Identical for PWIA or Spectral Function